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Spectral and photoelectric characteristics of the gamma irradiated *intrinsic oxide*–InSe heterostructures obtained under different conditions

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HIGHLIGHTS

- Influence of γ-quanta on *intrinsic oxide*–InSe HSs oxidized for 15, 60 min and 96 h were studied.
- Intrinsic oxide films are found to be low-sensitive to all fluences of γ-irradiation.
- Irradiation has not significant effect on the shape of the $\eta(h\nu)$ spectra.
- In vast majority cases an improvement of the V_{oc}, J_{sc}, S_V, S_I values for irradiated HSs was found.
- The *intrinsic oxide*–InSe HSs show a high resistance to γ-radiation.

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ABSTRACT

The investigations of photoelectric characteristics and photoresponce spectral dependences were carried out for *intrinsic oxide*–InSe heterostructures (HSs) and their changes induced by bremsstrahlung γ-quanta with an energy of 1–34 MeV at fluences of 10^{12}–10^{15} cm^{-2}. The thermal oxidation of the *p*-InSe:Cd substrates was carried out at a temperature of 420 °C. For three selected groups of samples the duration of the process was 15 min, 60 min, and 96 h. At a short-term oxidation (15 and 60 min) a layer of In_2O_3 appears. The only difference between the samples of these two groups is a higher photosensitivity in the range of energy 1.25–2.8 eV of the HSs obtained after the 60 min oxidation. At the long-term oxidation the photoresponce spectra $\eta(h\nu)$ of the obtained HSs are characterized with a sharp short-wavelength decrease at $h\nu \cong 2.0$ eV. It is established that the intrinsic oxide films act as transparent barrier electrodes in the corresponding HSs and are low-sensitive to γ-irradiation in the all range of fluences. The shape of the photoresponce spectra for all the gamma irradiated HSs remains practically the same. However, it was found: (i) some decrease of photosensitivity at the long-wavelength edge, (ii) decreasing the width of $\eta(h\nu)$ at half-height, (iii) the appearance of the exciton peak, (iv) the improvement of a slope of the low-energy edge of the photoresponce spectra with increasing irradiation dose whereas at the maximum fluence this parameter decreases, and (v) the slight extension of the spectral sensitivity to the short-wavelength range for the structures obtained after oxidation for 96 h. The photoelectric parameters of the *intrinsic oxide*–*p*-InSe HSs, open circuit voltage V_{oc}, short-circuit current J_{sc}, current $S_{I\lambda max}$ and voltage $S_{V\lambda max}$ sensitivities become only improved after irradiation with the fluences 10^{12}–10^{13} cm^{-2}. At the maximum fluence a small decreasing of the values of V_{oc} and J_{sc} was detected except for the structures obtained after oxidation for 15 min. An increase of the $S_{I\lambda max}$ and $S_{V\lambda max}$ sensitivities in comparison with the initial value were found for all the HSs even at the maximum fluence except for the structures obtained by a long-term oxidation.

1. Introduction

At present, the available commercial sensors of the visible, near-infrared, and ultra-violet and high-energy radiations in majority of the cases do not satisfy the criteria of radiation resistance. Conventional semiconductor electronics based on silicon fails already at moderate irradiation doses (Claeys and Simoen, 2002). Thus, there is a need to look for alternative materials.

As promising ones the layered crystals of the III–VI group, a typical representative of which is InSe, can be considered. Note that the energy gap of this semiconductor equals to 1.2 eV. This

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value is close to the energy gap of Si. However, due to the peculiarities of the crystal structure and chemical bonds in the different crystallographic directions layered compounds have unique physical properties different them from conventional semiconductors. In particular, weak Van der Waals bonds between the layers make it possible to produce easily plates of a necessary thickness with atomically smooth surfaces what makes the layered crystals promising materials for creation of new-type semiconductor devices (Feng et al., 2014; Lei et al., 2014; Shigetomi and Ikari, 2000). Besides unremitting attention to the III–VI semiconductors is caused by a possibility of their application for radiation-hardened photodetectors (Kovalyuk et al., 2007, 2009; Sydor et al., 2014) the detectivity of which is comparative to that of Si-based ones.

On contrary to the conventional procedure of the formation of *p*–*n*-junctions based on layered crystals, i.e. the creation of a direct optical contact between two layered compounds (Shigetomi and Ikari, 2000), a possibility of making high-quality jointless *intrinsic oxide*–InSe HSs by thermal oxidation in air seems to be interesting from the practical point of view. The intrinsic oxide film has conductive metallic properties, high mechanical strength and transparence to incident radiation. Besides the available experimental data on irradiation of a great amount of oxides, in particular In_2O_3, show that their radiation resistance is very high (Morgan et al., 1995).

In this paper the influence of bremsstrahlung γ-quanta with an energy of 1–34 MeV on photoelectric and spectral characteristics of *intrinsic oxide*–*p*-InSe HSs obtained oxidation for different time is under investigation.

2. Materials and methods

Growing single crystal ingots of the layered semiconductors was carried out by using vertical crystallization by the Bridgman method in a furnace with a two-section heater where a quartz ampule with a synthesized polycrystalline material was placed. For obtaining *p*-type conductivity indium monoselenide crystals were doped with 0.2 wt% Cd, which resulted in the following parameters: $p=(1–5)\times10^{14}$ cm^{-3} and $\mu_p=50–90$ cm^2 V^{-1} s^{-1} at 300 K. In addition the high-resistive Zn-doped InSe crystals were grown. They had a conductivity along the layers $\sigma_{\parallel C}$ $\sim7\times10^{-6}$ Ω^{-1} cm^{-1}. The ingots can be easily split onto separate plane-parallel planes with well-defined mirror-like cleaved surfaces.

For preparation of HSs the technique of thermal oxidation of the semiconductors was used. Oxidation of cleaved plates of layered crystals with dimensions about of $12\times6\times0.4$ mm^3 was carried out in an electrical furnace at a temperature 420 °C at free access of the air. Parameters of the oxide film as well as those of the HSs depend on time – temperature conditions of the technological process (Kovalyuk et al., 2004). The duration of thermal oxidation was 15, 60 min and 96 h for three groups of the samples.

The coloration of the intrinsic oxide films on the InSe substrates varied from invisible to dark-violet depending on process duration. The films are characterized with a thickness about of 8, 10 and 300 nm obtained after an oxidation for 15, 60 min and 96 h, respectively.

The oxidized samples were halved along a natural cleavage plane and cut off along their perimeter to avoid shorting of *p*–*n*-junctions. The frontal electric contact to the oxide film was formed by thermal deposition of high-purity indium. The back contact was prepared by soldering pure indium, which well moistens the semiconductor surface. The area and thickness of *intrinsic oxide*–*p*-InSe HSs were about of 0.3 cm^2 and 100 μm. Its schematic drawing is shown in the insert of Fig. 1.

The room temperature irradiations of the obtained HSs with

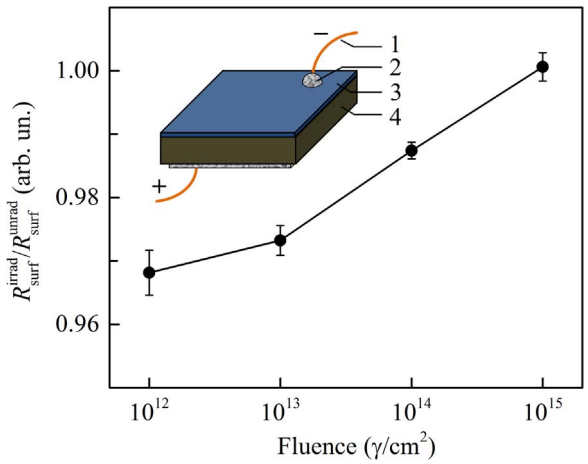

Fig. 1. Surface resistance vs γ-irradiation fluence for the intrinsic oxide film obtained by oxidation during 96 h of InSe:Zn substrate. Inset – a scheme of the investigated structures: 1 – copper wire, 2 – indium ball contact, 3 – intrinsic oxide film, 4 – indium selenide.

bremsstrahlung γ-quanta have been carried out in the electrostatic electron accelerator KUT-30 at an electron energy of 35 MeV and the average beam current of 250 mA. The electron beam was converted into bremsstrahlung on a tantalum target. For irradiation with γ-quanta the samples were placed at an angle of 90° with respect to the incident electron beam. The minimum cutoff energy of the gamma rays was 1 MeV so γ-irradiation energy ranged from 1 to 34 MeV. The duration of exposure was chosen so as to provide a necessary fluence of γ-quanta ranging from 10^{12} to 10^{15} cm^{-2} that equals to doses 14 Gy–14 kGy. The spectrum of γ-quanta from a thick tantalum converter was calculated by means of a software GEANT and is shown in Fig. S1 in Supplementary information.

Photocurrent spectra were registered by using an MDR-23 monochromator at room temperature. The spectral distribution of photoresponce was established from the ratio of phocurrent to number of incident photons. The spectral sweep has been carried out with a step not more than 200 nm.

3. Results and discussion

In order to establish the effect of high-energy γ-irradiation on the intrinsic oxide film, measurements of the surface resistance were carried out in dependence on γ-quanta fluence (Fig. 1). The investigated films were prepared on plates of InSe:Zn. The measurements of surface resistance R_{surf} have shown that a conductive film with the resistance ranging between 220 and 240 Ω/sq. for the different samples appeared after oxidation during 96 h. It is found that at the initial fluences (10^{12}–10^{13} cm^{-2}) the resistance of the irradiated film changes slightly (by 3%). At subsequent irradiation there are no essential variations in the value of R_{surf}. So, one can conclude that the intrinsic oxide films created by the method of thermal oxidation of InSe act as a transparent barrier electrode in the investigated HSs and are low-sensitive to γ-radiation.

Spectral dependences of photoresponce $\eta(h\nu)$ of the *intrinsic oxide*–*p*-InSe HSs are shown in Fig. 2(a). They have a form of a band restricted at the both sides typical for HSs. The wavelength range of the spectral characteristic in which its photosensitivity is not less than 10% of its maximum value, i.e. the range of spectral sensitivity $\Delta\lambda$ was < 0.30–1.03, 0.33–1.01, and 0.56–1.01 μm with the maxima at $\lambda_{max}=0.50$, $\lambda_{max}=0.50$, and $\lambda_{max}=0.66$ μm for the unirradiated HSs obtained for 15 min, 60 min, and 96 h oxidation, respectively. The $\eta(h\nu)$ spectra are characterized by an increase in